

## SOLID OXIDE AUXILIARY POWER UNIT REFORMATE CONTROL

## TECHNICAL FIELD

The present disclosure relates to mass flow control of a reformat for a solid oxide fuel cell.

## BACKGROUND

Alternative transportation fuels have been represented as enablers to reduce toxic emissions in comparison to those generated by conventional fuels. At the same time, tighter emission standards and significant innovation in catalyst formulations and engine controls has led to dramatic improvements in the low emission performance and robustness of gasoline and diesel engine systems. This has certainly reduced the environmental differential between optimized conventional and alternative fuel vehicle systems. However, many technical challenges remain to make the conventionally fueled internal combustion engine a nearly zero emission system having the efficiency necessary to make the vehicle commercially viable.

Alternative fuels cover a wide spectrum of potential environmental benefits, ranging from incremental toxic and carbon dioxide (CO<sub>2</sub>) emission improvements (reformulated gasoline, alcohols, LPG, etc.) to significant toxic and CO<sub>2</sub> emission improvements (natural gas, DME, etc.). Hydrogen is clearly the ultimate environmental fuel, with potential as a nearly emission free internal combustion engine fuel (including CO<sub>2</sub> if it comes from a non-fossil source). Unfortunately, the market-based economics of alternative fuels, or new power train systems, are uncertain in the short to mid-term.

The automotive industry has made very significant progress in reducing automotive emissions in both the mandated test procedures and the "real world". This has resulted in some added cost and complexity of engine management systems, yet those costs are offset by other advantages of computer controls: increased power density, fuel efficiency, drivability, reliability, and real-time diagnostics.

Future initiatives to require zero emission vehicles appear to be taking us into a new regulatory paradigm where asymptotically smaller environmental benefits come at a very large incremental cost. Yet, even an “ultra low emission” certified vehicle can emit high emissions in limited extreme ambient and operating conditions, with failed, or degraded components.

One approach to addressing the issue of emissions is the employment of electrochemical cells or fuel cells, particularly solid oxide fuel cells (“SOFC”), in an automobile. A fuel cell is an energy conversion device that generates electricity and heat by electrochemically combining a gaseous fuel, such as hydrogen, carbon monoxide, or a hydrocarbon, and an oxidant, such as air or oxygen, across an ion-conducting electrolyte. The fuel cell converts chemical energy into electrical energy.

A SOFC may be used in conjunction with a reformer that converts a fuel to hydrogen and carbon monoxide (the reformat) usable by the fuel cell. Three types of reformer technologies are typically employed (steam reformers, dry reformers, and partial oxidation reformers) to convert hydrocarbon fuel (methane, propane, natural gas, gasoline, etc.) to hydrogen using water, carbon dioxide, and oxygen, respectfully, with byproducts including carbon dioxide and carbon monoxide, accordingly. These reformers typically operate at high temperatures. At lower temperatures, e.g., during start-up, deposition of carbon (or soot) upon the catalyst can adversely affect the reformer efficiency and reduce reformer life. Major requirements for the reformers are rapid start, dynamic response time, fuel conversion efficiency, size, and weight.

Various methods of introducing the reformat to the SOFC have been utilized. These methods typically include direct interfaces or restrictive orifice between the reformer and the SOFC. Typically, a restrictive orifice is employed. Such a configuration however, lacks the ability to adequately regulate the amount of reformat that is applied to the SOFC to control the SOFC output.

What is needed in the art then, is method and apparatus, which allows the regulation of the reformat delivered to a SOFC.

## SUMMARY

A method and system for controlling reformat delivered to an electrochemical cell in an electric power system. The system comprises: a reformat pressure sensor disposed in the reformat and configured to measure reformat pressure; a controllable valve configured to control the flow of  
5 reformat to the electrochemical cell; and a controller coupled to the reformat pressure sensor and the controllable valve. The controller receives a reformat pressure signal from the reformat pressure sensor, a controllable valve position signal from the controllable valve, and transmits a controllable valve command to the controllable valve.

## BRIEF DESCRIPTION OF THE DRAWINGS

10 Referring now to the accompanying drawings, which are meant to be exemplary not limiting, and wherein like elements are numbered alike in the several figures.

Figure 1 is a block diagram depicting a typical reformer and SOFC system of an auxiliary power unit.

15 Figure 2 is a block diagram depicting an embodiment with a reformer and SOFC system employing dynamic pressure controls.

Figure 3 is a flow diagram depicting a dynamic pressure control algorithm.

20 Figure 4 is a block diagram depicting an alternative embodiment with a reformer and SOFC system employing dynamic flow controls.

Figure 5 is a flow diagram depicting a dynamic flow control algorithm.

## DESCRIPTION OF THE PREFERRED EMBODIMENT

Different types of SOFC systems exist, including tubular or planar systems. These various systems employ a variety of different cell  
25 configurations. Therefore, reference to a particular cell configuration and components for use within a particular cell configuration are intended to also represent similar components in other cell configurations where applicable.

FIG. 1 depicts a portion of a typical power system 10 employing a SOFC 50 and a reformer 20. Fuel is supplied to the reformer 20, and processed resulting in a reformat 102, which is supplied to the SOFC 50. The reformat 102 is typically metered and controlled via a fixed orifice or valve 40, which restricts the flow of the reformat 102 to the SOFC 50. Generally, power systems 10 may comprise at least one SOFC 50, an engine, and one or more heat exchangers. In addition, a power system 10 may include one or more compressors, an exhaust turbine, a catalytic converter, preheating device, an electrical source (e.g., battery, capacitor, motor/generator, or turbine), and conventional connections, wiring, control valves, and a multiplicity of electrical loads, including, but not limited to, lights, resistive heaters, blowers, air conditioning compressors, starter motors, traction motors, computer systems, radio/stereo systems, and a multiplicity of sensors and actuators, and the like, as well as conventional components. In addition, the SOFC 50 may also be electrically connected with other electrochemical cells or SOFCs.

To facilitate the production of electricity by the SOFC 50, a direct supply of simple fuel, e.g., hydrogen, carbon monoxide, and/or methane is preferred. However, concentrated supplies of these fuels are generally expensive and difficult to store and supply. Therefore, the fuel utilized may be obtained by processing of a more complex fuel. The actual fuel utilized in the system is typically chosen based upon the application, expense, availability, and environmental issues relating to a particular fuel. Possible fuels may include conventional fuels such as hydrocarbon fuels, including, but not limited to, conventional liquid fuels, such as gasoline, diesel, ethanol, methanol, kerosene, and others; conventional gaseous fuels, such as natural gas, propane, butane, and others; and alternative or "new" fuels, such as hydrogen, biofuels, dimethyl ether, and others; as well as combinations comprising at least one of the foregoing fuels. The preferred fuel is typically based upon the type of engine employed, with lighter fuels, i.e., those which can be more readily vaporized and/or conventional fuels which are readily available to consumers, generally being preferred.

Furthermore, the fuel for the SOFC 50 may be processed in a reformer 20. A reformer 20 generally converts one type of fuel to another, more compatible with the SOFC 50 (e.g., hydrogen). Mainly, two types of reformer technologies are employed; steam reformers, which employ exothermic  
 5 reaction, and partial oxidation reformers, which employ an endothermic reaction. Steam reformer technology is generally employed for converting methanol to hydrogen. Partial oxidation reformers are generally employed for converting gasoline to hydrogen. Typical considerations for the reformers include rapid start, dynamic response time, fuel conversion efficiency, size, and  
 10 weight.

The SOFC 50 may be used in conjunction with an engine, for example, to produce tractive power for a vehicle. Within the engine, SOFC effluent, air, and/or fuel are burned to produce energy, while the remainder of unburned fuel and reformed fuel is used as fuel in the SOFC 50. The engine  
 15 can be any conventional combustion engine including, but not limited to, internal combustion engines such as spark ignited and compression ignited engines, including, but not limited to, variable compression engines.

FIG. 2 depicts a block diagram of an embodiment of the invention as interposed in a power system 10. A reformer 20 processes fuel  
 20 generating a reformat 102. A reformat pressure sensor 22 measures the reformat pressure and generates a reformat pressure signal 104, which is transmitted to a controller 30. The reformat 102 flows to the SOFC 50 via a controllable valve 60. The controllable valve 60 is configured to receive a controllable valve command 108 from the controller 30. The controllable valve  
 25 60 also includes a position sensor (not shown), which detects the position of the valve and transmits the measured controllable valve position signal 106 representative of that position to the controller 30.

In order to perform the prescribed functions and desired processing, as well as the computations therefore (e.g., the execution of pressure  
 30 control algorithm(s), and the like), controller 30 may include, but not be limited to, a processor(s), computer(s), memory, storage, register(s), timing, interrupt(s), communication interfaces, and input/output signal interfaces, as

well as combinations comprising at least one of the foregoing. For example, controller 30 may include signal input signal filtering to enable accurate sampling and conversion or acquisitions of such signals from communications interfaces. Additional features of controller 30 and certain processes therein are  
5 thoroughly discussed at a later point herein.

As exemplified in a disclosed embodiment as depicted in FIGs. 2 & 3, one such process may be controlling the position of the controllable valve 60 in response to various system parameters. Controller 30 receives various input signals including, but not limited to, those identified above, to facilitate  
10 such processing and may provide one or more output signals in response. In an embodiment, the controller 30 receives as input signals: a desired reformate pressure signal 110 representative of the desired reformate pressure, the reformate pressure signal 104, the measured controllable valve position signal 106, and transmits as an output a controllable valve command 108.

15 Referring now to FIG. 3, an exemplary depiction of a pressure control algorithm is provided. The reformate pressure signal 104 is compared with the desired reformate pressure signal 110 at pressure comparator 210 to formulate a reformate pressure error signal. A desired position for the controllable valve 60 is determined in response to the reformate pressure error  
20 signal. In an embodiment, if the reformate pressure error is greater than a first pressure error threshold, a desired controllable valve position value 220 is decreased. Likewise, if the reformate pressure error is less than a second pressure error threshold, the desired controllable valve position value 220 is increased. Thereby, a new desired controllable valve position value 220 is  
25 generated. In an exemplary embodiment, the pressure error thresholds for both comparisons are set at zero. However, it will be appreciated that a variety of thresholds may be envisioned based on the desired operational characteristics. For example, providing for operational dead-band or hysteresis to simplify controller functions. Also of note, the increase or decrease in the desired  
30 controllable valve position value 220 may include, but not be limited to, such functions as a look-up table, scaling, counters, and/or other implementation methodologies for adjusting the set point for the desired controllable valve

position value 220. The new desired controllable valve position value 220 of the controllable valve 60 may be compared to the measured controllable valve position signal 106. The comparison at valve position comparator 230 yields a difference between the desired and measured positions, which is a valve position error. The valve position error is then compared to a first position error threshold and a second position error threshold to ascertain if an adjustment in the controllable valve command 108 is warranted.

For example, if the valve position error is greater than the first position error threshold, the controllable valve command 108 is decreased, thereby reducing the controllable valve position and causing the controllable valve 60 to close a predetermined increment. Likewise, if the valve position error is less than the second position error threshold, the controllable valve command 108 is increased, thereby increasing the controllable valve position and causing the controllable valve to open a predetermined increment. In such a manner, a closed loop control of the pressure to the SOFC 50 is achieved. For example, if the measured pressure 104 of the reformat is too high, the subtraction at pressure comparator 210 generates a reformat pressure error signal, which if it is less than the second pressure error threshold, increases the desired controllable valve position value 220. The increased desired controllable valve position in turn, causes an increase on the controllable valve command 108, thereby resulting in an increase in the controllable valve position, opening the controllable valve 60, causing a decrease in the pressure of the reformat supplied to the SOFC 50.

As stated earlier, relating to the pressure error threshold, it will once again be appreciated that a variety of thresholds may be envisioned. Likewise, once again, the modification of the controllable valve command 108 may include, but not be limited to, such functions as a look-up table, scaling, counters, and/or other implementation methodologies for adjusting the set point for the desired controllable valve position.

In addition to control of controllable valve 60, the measured reformat pressure signal 104 may further be employed in a diagnostic algorithm to facilitate evaluation of proper operation of the reformer 20 and

controller 30. For example, the measured reformat pressure signal 104 is compared with a predictive pressure for the operating conditions of the reformer 20. If the comparison should yield an error beyond a predetermined tolerance, corrective measures may be implemented and/or a diagnostic flag may be set to signal the presence of a malfunction.

It is noteworthy to appreciate that, employing the method disclosed herein, as the operational characteristics of system components dynamically change, the pressure control system likewise, modifies its parameters accordingly. Therefore, changes in system performance due to downstream system degradation may be automatically accounted for and compensated. Likewise, other system variances, which may not have been addressed, may set a system diagnostic flag, prompting corrective measures.

FIG. 4 depicts a block diagram of an alternative embodiment on as interposed in a power system 10. In this embodiment, a mass flow control system similar to the abovementioned pressure control system is disclosed. Similar to the pressure control system depicted in FIG. 2, the reformer 20 processes fuel generating a reformat 102. The reformat pressure sensor 22 measures the reformat pressure and generates a reformat pressure signal 104, which is transmitted to controller 30. The controllable valve 60 meters the reformat 102 as it flows to the SOFC 50. The controllable valve 60 is configured to receive the controllable valve command 108 from the controller 30. The controllable valve 60 also includes the position sensor (not shown), which detects the position of the valve and transmits a measured controllable valve position signal 106 representative of that position to the controller 30. An SOFC pressure sensor 24 measures the pressure of the metered reformat 112 and generates a metered reformat pressure signal 114, which is transmitted to controller 30.

Turning now to FIG. 5, as well as FIG. 4, a mass flow control algorithm is depicted. The mass flow control algorithm again, is similar to the pressure control algorithm of FIG. 3, with the exception of including processing for the metered reformat pressure signal 114. In this embodiment, the reformat pressure signal 104 is compared with the metered reformat pressure



signal 114 at difference 402 to formulate a pressure differential signal. The pressure differential signal is converted to an actual mass flow signal 406 utilizing a look up table 404, which is indexed by the pressure differential signal. The actual mass flow signal 406 evaluated versus a theoretical mass flow signal at mass flow comparator 410 to determine a mass flow error signal. A desired controllable valve position value 220 for the controllable valve 60 is determined, responsive to the mass flow error signal.

It will be appreciated that while the disclosed embodiments refer in several instances, to a configuration utilizing look-up tables in implementation, such a reference is illustrative only and not limiting, various alternatives will be apparent to those skilled in the art. For example, the processes described above could employ, in addition to or in lieu of look-up tables, direct algorithms, gain or parameter scheduling, linearized interpolation or extrapolation, and/or various other methodologies, that may facilitate execution of the desired functions.

In an embodiment, if the mass flow error is greater than a first mass flow error threshold, the desired controllable valve position value 220 is decreased. Likewise, if the mass flow error is less than a second mass flow error threshold, the desired controllable valve position value 220 is increased. Thereby, a new desired controllable valve position value 220 is generated. Similar to the previously disclosed embodiment, the predetermined thresholds for both comparisons are set at zero. Again, it will be appreciated that a variety of thresholds are possible. Also of note, once again, the method of determining the desired controllable valve position 200 may include the same variations as disclosed earlier.

The new desired controllable valve position value 220 of the controllable valve 60 may be compared to the measured controllable valve position signal 106. The comparison at valve position comparator 230 yields a difference between the desired and measured positions, which is a valve position error. The valve position error is then compared to a set of predetermined thresholds to ascertain if an adjustment in the controllable valve command 108 is warranted.

In an embodiment, if the valve position error is greater than a third position error threshold, the controllable valve command 108 is decreased causing the controllable valve 60 to close a predetermined increment. Likewise, if the valve position error is less than a fourth position error threshold, the controllable valve command 108 is increased causing the controllable valve to open a predetermined increment. Thereby, control of the mass flow to the SOFC 50 is achieved. For example, if the actual mass flow signal 406 of the reformat is too high, the subtraction at mass flow comparator 410 generates a mass flow error signal, which if it is less than the fourth position error threshold, increases the desired controllable valve position value 220. The increased desired controllable valve position in turn, causes an decrease on the controllable valve command 108, thereby resulting in a decrease in the position and closing of the controllable valve 60 resulting in a decrease in the mass flow of the reformat supplied to the SOFC 50. Similar to the previous disclosures, it will be appreciated once again, that a similar variety of thresholds may be envisioned. In a manner similar to the previous case, the method of determining the controllable valve command 108 may include may include the same variety of characteristics as disclosed earlier.

Similarly, like the pressure control case, in the alternative embodiment, the actual mass flow signal 406 may further be employed in a diagnostic algorithm to facilitate proper operation of the reformer 20 and controller 30. For example, the actual mass flow signal 406 is compared with a predictive mass flow for the operating conditions of the reformer 20. If the comparison should yield an error in beyond a predetermined tolerance, corrective measures may be implemented and/or a diagnostic flag may be set to signal the malfunction.

It is noteworthy to appreciate that, employing the method disclosed herein, as the operational characteristics of system components dynamically change, the mass flow control system likewise, modifies its parameters accordingly. Therefore, changes in system performance due to downstream system degradation may be automatically accounted for and

compensated. Likewise, other system variances, which may not have been addressed, may set a system diagnostic flag, prompting corrective measures.

The disclosed method may be embodied in the form of computer-implemented processes and apparatuses for practicing those

5 processes. The method can also be embodied in the form of computer program code containing instructions embodied in tangible media, such as floppy diskettes, CD-ROMs, hard drives, or any other computer-readable storage medium, wherein, when the computer program code is loaded into and executed by a computer, the computer becomes an apparatus capable of executing the  
10 method. Additionally, the method can also be embodied in the form of computer program code, for example, whether stored in a storage medium, loaded into and/or executed by a computer, or as data signal transmitted whether a modulated carrier wave or not, over some transmission medium, such as over electrical wiring or cabling, through fiber optics, or via electromagnetic  
15 radiation, such that, when the computer program code is loaded into and executed by a computer, the computer becomes an apparatus capable of executing the method. When implemented on a general-purpose microprocessor, the computer program code segments configure the microprocessor to create specific logic circuits.

20 Therefore, the foregoing disclosure provides in multiple embodiments, methodologies and systems for controlling the reformat applied to an electrochemical cell. Moreover, the same methodologies could be applied to the control of hot gases delivered to an engine, for example an internal combustion engine. Finally, diagnostic methodologies are disclosed that allow  
25 for evaluation of operational characteristics and provide a means for detecting malfunctions and leaks in the system.

While preferred embodiments have been shown and described, various modifications and substitutions may be made thereto without departing from the spirit and scope of the invention. Accordingly, it is to be understood  
30 that the present invention has been described by way of illustration only, and such illustrations and embodiments as have been disclosed herein are not to be construed as limiting to the claims.